3D Printing Process for Patient-Specific Models and Applications

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Abstract

In the past decade, 3D printing has emerged as a game-changing technology in medicine, particularly in the creation of patient-specific models and applications. Patient-specific models are generated from medical imaging data (such as CT scans or MRI), allowing for precise replication of a patient's anatomy. Modeling software helps visualize, analyze, and modify data, ensuring its accuracy and providing valuable insights for decision-making and problem-solving. This article explores the 3D printing processes that are used to create patient-specific models tailored to the unique anatomical and medical needs of individuals. The ability to produce highly accurate and customized models have improved surgical outcomes, reduced risks, and accelerated innovation. The applications include presurgical planning, prosthetics design, implant development, medical device advancement, and education for healthcare professionals. This article will also explore how the 3D printing process improves our understanding of the medical applications of various techniques such as material extrusion, vat polymerization, and powder bed fusion. 3D printing materials offer a variety of properties, including flexibility, rigidity, and cellular structures, making them suitable for a wide range of applications, despite the challenges of material limitations, cost, and ambiguous regulations. In the future, point-of-care in healthcare will rely on the potential of 3D printing to transform medical practice by providing personalized, patient-centered care through innovative applications of additive manufacturing technology.

Keywords: 3D printing technology, Medical 3D printing, Patient-specific model, Additive manufacturing

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Introduction

3D printing technology is an additive manufacturing process that generates a physical object from a digital model, using a layer by layer method. It is widely used not only in the medical field but also in other industries such as customized design and jewelry.[1-3] In healthcare, 3D printing plays an important role for personalized solutions to produce implants, prosthetics, and equipment such as ventilator valves, face shields, and swabs during the COVID-19 pandemic.[4] It can also make an anatomical model of a patient with detail and accuracy.[5] An anatomical model can be used in preoperative surgical planning, such as analysis and diagnosis formulation, especially in complex cases. Moreover, it can be used as a visual tool for explaining concepts to patients, helping them better understand and cooperate with their treatment processes.[6, 7] All kinds of models can be created by various types of materials, including soft and hard properties, as well as biomaterials.[8] Advantages in this process are customized production, freeform design, and cost-effectiveness. Hence, 3D printing provides a convenient way to build complex shapes while using less material than traditional manufacturing methods. In medical 3D printing at hospitals or the point-of-care, doctors and specialists, such as biomedical engineers or radiologists, must work together and collaborate to accomplish the same goal. Therefore, an understanding of the process is useful for optimizing the work plan to minimize errors and miscommunication throughout the process. This encourages collaboration across all clinical specialties, leading to better solutions in healthcare, particularly in personalized treatment. By integrating 3D modeling and advanced technologies, physicians can tailor treatments to the unique needs of each patient, improving outcomes and enhancing patient care.

Manufacturing Process of Patient-Specific 3D Printing

In the manufacturing process, the group of people involved consists of physicians, biomedical engineers, and other technicians. Each process requires specific skills to ensure the efficiency of the desired outcome. There are 5 steps for manufacturing a 3D physical object, using patient-specific data (Figure 1).

1) Patient Imaging and Model Data

Digital Imaging and Communication in Medicine, also known as DICOM, is provided with information about patients, imaging equipment, procedures, and images from various modalities such as x-rays, computed tomography (CT), and magnetic resonance imaging (MRI). The DICOM standard specifies a diverse range of information and is used in many fields and interventions.[9] A DICOM file contains raw data that requires special software to convert it into 3D models for simulation, diagnosis, or surgical planning.[10, 11] In design and engineering, computer-aided design (CAD) is a tool that uses computer-based software to aid in the creation, modification, analysis, and optimization of a design. A custom 3D model for a specific purpose or device can be simulated as a part or assembly with another model before the manufacturing process. The 3D graphic model, DICOM data, and CAD can be used together in the next process, which involves 3D modeling software.

2) Model Modification and File Conversion

3D modeling is the process of using software for modification, analysis, and optimization of a 3D object or model. For example, it can be used to design and simulate a screw for a bone fixture plate in a medical device. For this purpose, DICOM images are segmented into a 3D CAD format for intermediate data. In healthcare, modeling software may require high standards for specific purposes, such as creating a medical model for diagnosis. Medical 3D modeling software enables the creation of patient-specific models for conditions or diseases tailored to an individual's unique anatomy. These models are valuable in diagnosis, treatment planning, and surgical procedures. In diagnosis, medical models are considered medical devices and are subject to regulations. For instance, software can display 2D and 3D anatomical reconstructions for disease diagnosis or surgery planning. If used as implants, the software must comply with Food and Drug Administration (FDA) standards to ensure safety and quality. The FDA recognizes 3D-printed anatomical models that influence diagnosis or patient treatment as diagnostic tools. Modeling software, including Materialise Mimics InPrint, Synopsys Simpleware ScanIP Medical, RICOH 3D for Healthcare, and Axial3D Cloud Segmentation Software, have FDA clearance for diagnostic use.[12] These modeling software solutions can be used for diagnostic purposes in orthopedic, maxillofacial, and cardiovascular applications.

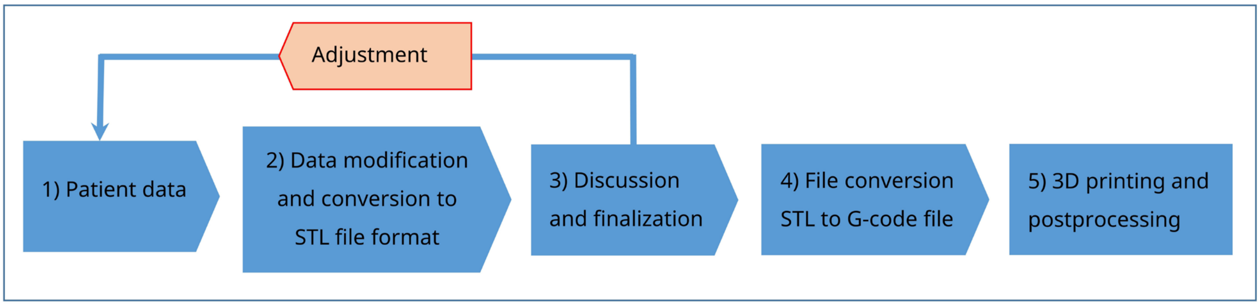
3) Data Finalization and Communication

In the overall process, physicians, engineers, and other technicians work together to create accurate medical models. Typically, the physician presents a clinical problem along with patient image data while biomedical engineers or scientists are involved with data modification and manufacturing. Communication among team members regarding the target goal is very important. However, misunderstandings, along with missing information such as slice thickness, noise, and resolution, can impact the workflow. A printing process consumes a long time, especially with complex models. Therefore, all steps of the process require clear discussion and finalization along with addressing technical issues with the physician to ensure the desired outcome and optimized time planning.

4) Conversion of Standard Triangle Language (STL) to G-code (Slicing)

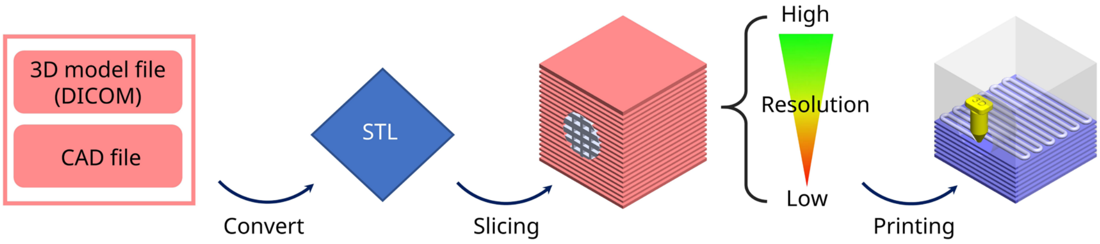
3D printing is a process that generates a 3D object by forming layers of material under computer control to create a physical object. The 3D medical model or CAD file is usually sliced into several layers, depending on the layer thickness or resolution of slicing (Figure 2). The number of slices represents both the quality of the input image data and the quality of the final object. In complex structures, 3D printing can produce almost any shape or geometry that is difficult or impossible to achieve with traditional manufacturing methods.

Figure 1. Schematic of Process in Patient-Specific 3D Printed Model



Abbreviation: STL, standard triangle language.

Figure 2. Slicing Process for 3D Model



Abbreviations: CAD, computer-aided design; DICOM, Digital Imaging and Communication in Medicine; STL, standard triangle language.

5) Type of 3D Printing Technology

3D printing technologies have transformed manufacturing by providing various methods for creating parts tailored to specific applications. There are 2 types of 3D printers available in the market: desktop-grade and industrial-grade printers. Desktop 3D printers are designed for home or small-scale printing and are cost-effective, whereas industrial 3D printers are more expensive and used for large-scale production. A category of the main technologies includes 3 types: material extrusion, vat polymerization, and powder bed fusion.

5.1) Material Extrusion

Fused filament fabrication (FFF), also known as fused deposition modeling (FDM), is a material extrusion methodology for the 3D printing process. Thermoplastic filament is heated and extruded to create 3D objects, layer by layer. It is one of the most popular additive manufacturing techniques due to its simplicity and cost-effectiveness. There are various thermoplastic materials with both rigid and flexible properties for FFF 3D printing, as well as a wide range of material colors from different brands. In the printing process, a support structure is almost always required to help with overhangs or to stabilize parts.[13] According to low resolution technology, a small detail or thin layer may not be printed or distinguished from a simple extrusion, such as some details of an anatomical model from a DICOM file. After the printing process, postprocessing is required, mainly involving support removal and surface finishing.

Visualization, combined with FDM 3D printing, enhances understanding in surgical planning and education by allowing students to observe the differences between normal and abnormal patient models.[14] Cost-effective printing, using thermoplastic polyurethane (TPU) material, is employed to model abdominal aortic aneurysm geometry, particularly for practicing the placement of hooked or barbed stents.[15] One of the interesting materials in the FFF method is polyetheretherketone (PEEK), which has biocompatible and high-performance properties.[16] The clinical application and outcomes of FDM rib prostheses fabricated from PEEK are detailed as a material closely resembling natural costal cartilage.[17-19] Preoperative CT scans identified rib tumors, necessitating surgical resection and prosthesis implantation. Intraoperative observations showed the prostheses secured with steel wires. Postoperative CT scans confirmed successful integration, alignment, and stability of the implants, demonstrating PEEK's effectiveness for reconstructing rib and costal cartilage structures in clinical settings.

In advanced medicine, there has been an increased shift towards precision medicine. Today, the production of oral pharmaceutical forms tailored to patients is not achievable by traditional industrial methods.[20] FDM, with its high adaptability, can provide specific solutions for many personalization requirements in drug development research and precision medicine.[21, 22]

5.2) Vat Polymerization

Vat polymerization is a method for printing 3D objects using photopolymerization. It is a polymerization reaction in which molecules in the liquid state convert to solid macromolecules through light as an energy source. Vat polymerization technology includes stereolithography (SLA), digital light processing (DLP) and masked stereolithography (MSLA). SLA was the first 3D printing technology developed in the 1980s by Hull.[23] It uses a vat polymerization method with a photopolymer resin in the 3D printing process.

Ultraviolet (UV) light is selectively used for curing and hardening to initiate a reaction on the resin layer, forming a solid printing layer. Typically, SLA uses an ultraviolet laser beam while DLP and MSLA use a digital light projector and light emitting diode (LED) light, respectively. They are based on the same technique but differ in the light source, while maintaining good quality. However, all of them are still called "SLA" to avoid confusion and promote simplification for marketing. SLA offers high resolution, high accuracy, isotropy, watertightness, and the smoothest surface finishes. This is a great choice for creating visual prototypes. The liquid photopolymer resin materials are soft, hard, and clear photopolymers, including biocompatible resins. A support structure, which is one of the factors for successfully producing 3D-printed parts, is always required in SLA. After the printing process, the part is not in a fully cured state, with incomplete polymerization and full mechanical properties not yet reached. In the postprocessing, a printed part needs to be cleaned with isopropyl alcohol (IPA) to remove any residue of liquid resin. UV postcuring is used to enhance the full mechanical properties and other characteristics of the finished part. A fully cured part is more brittle, which may make it unsuitable for functional prototypes. The final postprocessing steps of SLA are support removal and surface finishing. This process requires additional tools, a UV curing chamber, and time to achieve the desired outcome.

In personalized medical implants, it demonstrates the 3D design and manufacturing of patient-specific endocardial implants.[24] In prosthesis, SLA technology appears to be a clinically suitable process for fabricating resin prostheses. The proper printing or scanning conditions are important for optimizing the prosthesis fit for the patient.[25, 26] In dental research, SLA enhances traditional methods for dental implants by providing more precise and efficient techniques and materials. Additionally, an alternative study on materials, specifically ceramic-composite resin, impacts dental prosthetics by enabling the efficient and cost-effective production of high-performance, patient-specific restorations.[27]

5.3) Powder Bed Fusion

Powder bed fusion is a 3D printing technique that uses a bed of powdered material and a heat source, such as a laser or electron beam, to fuse or sinter the powder layer by layer. It is widely used in production, providing high precision for complexly designed parts. These are industrial 3D printers as follows.

Selective laser sintering (SLS) is a 3D printing technique that uses a laser to selectively sinter the particles of a polymer powder, fusing them together layer by layer until a complete object is formed. SLS is a versatile solution with isotropic properties and is cost-efficient for producing high-quality components in low to medium quantities. The materials used in SLS are thermoplastic polymers in powder form, with the most widely used being polyamide 12 (PA12), commonly known as nylon 12. Engineering plastics, such as polyamide 11 (PA 11) and PEEK, are also available but not widely used. During the printing process, an extra support structure is not required for SLS because the part is fully encapsulated in unmelted powder, making it self-supporting. Thus, SLS allows for the creation of more complex designs and free-form geometries without leaving marks on the printed part. After the printing process, the part and powder remain very hot. Additional time is required for the material to cool down in the powder bed before part removal. In the postprocessing, a printed part must be cleaned of residual powder, which can be reused for the next print. SLS-printed parts have a matte surface with internal porosity, which can be improved using postprocessing methods such as surface finishing or waterproof coating. SLS 3D printing technology offers innovative solutions for oral drug delivery by enabling the creation of customized, complex drug formulations with tailored dosages and release profiles.[28, 29] Using biocompatible materials, SLS can produce multilayered tablets or capsules that control drug release, potentially combining multiple drugs in one dosage form. In implantable patient-specific devices, biodegradable materials such as polycaprolactone (PCL) are used for pediatric airway support based on patient anatomical models.[30]

Electron beam melting (EBM) is a metal additive manufacturing process that uses a high-energy electron beam to melt metal powders in a vacuum chamber. A thin layer of metal powder is precisely melted and solidified layer by layer into the part's pattern design. The high-energy electron beam enables the rapid processing of materials, making EBM faster than many other 3D printing technologies. It can produce highly complex, detailed parts with high precision and resolution. EBM can work with high-melting-point metals, using materials in coarse powder form, to produce strong, dense, and lightweight parts. A commonly used material for EBM is titanium alloy Ti-6Al-4V, along with other alloys. In the printing process, no support structure is required due to self-support from unmelted powder. Despite its advantages, this technology involves significant equipment costs, including those for the vacuum chamber and the high-energy electron beam system, which may restrict accessibility for users. EBM deals with metals that require heat treatment during postprocessing. Moreover, the printed parts often have a rough surface finish due to the high power and size of the powder, but the desired smoothness can be achieved through surface finishing. The process primarily deals with conductive metals, with titanium and chromium-cobalt alloys being the most common, resulting in a rough surface finish. Titanium alloys have a high melting point and are particularly valued for their biocompatibility, lightweight nature, and high mechanical strength. Narra et al[31] describe a knee implant prototype fabricated using the EBM process with Ti-6Al-4V material. The implant's rough surface is engineered to improve bone formation indicators, promoting improved osseointegration.[32] This work underscores the potential of additive manufacturing for creating patient-specific implants with optimized surface properties, particularly in procedures like total joint arthroplasty, demonstrating the capability of tailored designs to improve clinical outcomes and advance the field of personalized medical implants.

Selective laser melting (SLM) is a metal additive manufacturing process that uses laser powder bed fusion. It is primarily used to produce metal parts with complex geometries that are difficult to create using traditional manufacturing techniques. A high-powered laser selectively melts the metal powder layer by layer into a solid form. SLM parts exhibit near-isotropic properties, depending on several factors such as the material, printing process, and postprocessing. Once a layer of metal is melted and solidified, the platform or build bed lowers by one level, and a new layer of metal powder is applied until the final layer. When the laser melts the metal powder, the high temperature causes the metal to vaporize. This vaporization leads to the formation of metal oxide fumes or metal vapor, which can condense into fine dust particles. The laser melting process begins with a bed of fine metal powder, typically made of titanium, aluminum, stainless steel, or other metals. SLM always requires supports during the printing process for stabilization, overhangs, and complex geometries. These structures help prevent collapse or failure during the process. After printing, the part typically requires a cooldown period, support removal, heat treatment, and some postprocessing steps. The residual powder can be reused in future prints. In addition, support removal may be difficult due to the complexity of the part, the type of supports used, and the material. Power tools such as rotary tools, milling machines, or wire electrical discharge machining, are required for part finishing. In bone implants, it is often difficult to fabricate implants that optimally fit a defect size or shape.[33] The production speed of SLM is quite slow due to the need to melt and solidify the material layer by layer. Scaffold-based designs are an alternative treatment. The assembled scaffold, made of SLM, is proposed with validation to quickly create a scaffold before implantation during surgery.[34] In dental application, titanium 3D metal implant was used occlusal rehabilitation using the concept of submerged that conventional dental implant was installed into titanium implant.[35]

Direct metal laser sintering (DMLS) is a metal additive manufacturing process that uses a laser to sinter metal, creating a solid part layer by layer. It is primarily used to create metal components that are complex in shape and require high precision and strength. A high-powered laser is used to selectively melt and fuse the metal powder particles together. The laser energy is carefully controlled to sinter the metal, causing the powder particles to bond without fully melting. DMLS and SLM follow almost identical steps in printing, such as material handling, heat treatment, support removal, and postprocessing, with the main difference being in the melting stage. DMLS uses a laser for partial melting, while SLM involves fully melting the material. DMLS parts have an advantage due to their unique structure, as they generally have a more porous structure compared to other metal 3D printed parts, such as those made with SLM, which are denser. In terms of strength, SLM parts are generally stronger than DMLS parts. In total hip replacement, cementless femoral stems made of titanium, which are stiffer than bone, are traditionally used in surgery. However, they can cause several complications, such as poor bone ingrowth, stress shielding, and an increased risk of bone fracture. A reduction in stiffness using DMLS can help minimize complications and increase the long-term success of the implant.[36] Varying stiffness can be designed to optimize performance for specific cases, including dental implants.[37, 38]

Material jetting is a 3D printing technology that involves the layer-by-layer deposition of liquid photopolymer materials through a print head, similar to inkjet printing. Drop-on-demand is a method in which material is selectively released. In the printing process, liquid photopolymer materials are jetted from the print head onto the build platform, where they are then cured by UV light to form solid layers. It offers high resolution, a smooth surface finish, multimaterial capabilities, fast production, and full color of 3D parts. The materials, which are thermoset photopolymer resins, have various properties, including rigidity, flexibility, and clarity. Each material has its own viscosity, which is an essential factor for proper flow control. Material jetting does not always require support for most parts; however, for overhangs and complex geometries, support material, which is a gel-like or wax substance, is required. Common types of supports, including water-soluble, breakaway, and dual-material supports, do not leave marks on the part’s surface. After the printing process, postprocessing of material jetting prints typically involves steps such as cleaning and surface finishing. However, the printed parts require additional curing under UV light to fully harden and enhance their mechanical properties. A surgical prototype created using material jetting technology is introduced, featuring bilateral flexible elastomeric strips designed for incision and sutureless wound closure.[39, 40] Made from thermoplastic and elastomeric resins, the device incorporates cutting guides and a wound closure mechanism, customizable for specific instruments to ensure mechanical reliability. Additionally, patient-specific 3D printed soft models are employed for surgical planning and hands-on training, particularly in complex pediatric liver surgeries, aiding navigation through intricate hepatic anatomy.[41]

Binder jetting is a 3D printing technique that selectively bonds particles of powdered material together using a liquid binder to create a solid part. It employs a drop-on-demand method to apply the liquid binder, similar to material jetting. In this approach, binder droplets are ejected only when needed, allowing precise control over where and how much binder is used. This improves material efficiency and enhances the quality of the final part. Binder jetting can use a variety of materials, including metals, ceramics, sand, composites, and plastics. However, plastic is less commonly used in binder jetting due to its higher cost and the availability of alternative printing technologies. Binder jetting offers great design freedom, as it does not require support structures. The parts are fully encapsulated and supported by the surrounding powder, which helps stabilize their structure, similar to SLS. After the printing process, parts need to cool and settle in the powder bed before removal. Postprocessing includes the debinding process, which eliminates the binder material, followed by sintering at high temperatures to fuse the powder particles together, increasing density and strength (for metal and ceramic parts). Surface finishing includes additional processes, such as grinding or polishing, to achieve a smoother surface. Binder jetting is preferred over SLM when the primary goals are cost-effectiveness, faster production speed, and the ability to print larger volumes or a variety of materials with sufficiently good mechanical properties. When comparing binder jetting and material jetting in terms of material cost, binder materials are generally cheaper than photopolymer materials. According to advanced technology, the end-to-end digital manufacturing solution employs a hybrid process that combines binder jet technology with automated dry post-machining to produce personalized magnesium implants for cranial applications.[42] This solution will help shorten production time and enable us to serve patients more efficiently in the future.

3D Printing of Biomaterials

Bioprinting is an advanced form of 3D printing technology that uses bioinks containing living cells to print tissues, organs, and other biological structures using a layer-by-layer technique. These layers are composed of living cells or cell-laden materials. The bioprinted structures are then cultured in a bioreactor or incubator to allow the cells to grow and form tissues. 3D bioprinting offers many advantages and has the potential to transform medicine, particularly in personalized healthcare, tissue engineering, and organ transplantation. The goal of 3D bioprinting is to create living, functional tissues for use in tissue engineering, drug testing and development, personalized medicine, regenerative medicine, and organ transplantation. However, creating fully functional bioprinted organs for organ transplants has not yet been successful. Bioinks, which are typically made from a combination of biocompatible materials such as hydrogels, collagen, alginate, and others, are used in 3D bioprinting to support cell survival and growth. Bioprinting often requires support structures during the printing process to stabilize the printed tissue and prevent collapse or overhangs before it solidifies or integrates with surrounding cells. 3D bioprinting faces several limitations that hinder its development and application, with one major challenge being the need to find bioinks that effectively mimic the properties of natural tissues, such as elasticity and biodegradability. Some research on bioink for patient-specific applications focus on creating customized tissues for regenerative medicine using patient-specific factors.[43, 44] Moreover, maintaining cell viability during and after the printing process is challenging, and integrating printed tissues with the surrounding biological environment is crucial. High costs associated with bioprinting technologies further limit accessibility for researchers and clinicians, while cell sourcing and the implications of organ printing raise ethical concerns.

Ethical Considerations of Medical 3D Print

Ethical considerations surrounding patient-specific 3D printing, such as creating customized implants, prosthetics, or even bioprinted tissues and organs, are critically important as this technology intersects with medicine, science, and personal well-being. These ethical concerns revolve around issues of privacy, informed consent, safety, equity, and the responsibility of using advanced technologies.[45, 46] Currently, 3D printing is becoming more widely used in healthcare and point-of-care.[47, 48] It is important to ensure that the benefits of the technology are realized while minimizing risks throughout all processes.

Conclusions

3D printing technology is an additive manufacturing process for creating 3D objects based on a layer-by-layer principle with computational design. Objects can be made from various types of materials, such as polymers or metals, with specific properties or biocompatible materials. The materials used in 3D printing come in difference form, such as filament, liquid, powder, and biomaterial. Choosing the right 3D printing method and material is crucial for ensuring quality. Each printing technique has unique benefits. Therefore, it is essential to understand the different 3D printing technologies, their characteristics, and how they align with the specific requirements of the work. The 3D printing process for a specific application or device helps streamline the workflow. 3D printing at the point-of-care transforms healthcare by enabling facilities like hospitals and clinics to produce medical devices, prosthetics, implants, and personalized treatments directly onsite. This innovation offers rapid, patient-specific solutions tailored to individual needs, eliminating the reliance on external manufacturers. 3D printing can reduce manufacturing costs by decreasing labor and shipping expenses and minimizing inventory needs. Furthermore, it is beneficial to have a biomedical engineer at the point-of-care because many ideas and technical challenges can be addressed and planned collaboratively. Future developments in 3D printing technology will enhance speed, introduce new materials, enable mass production, and improve cost efficiency in production. However, challenges such as regulatory approvals, training for healthcare professionals, quality control, and costs must be addressed for successful implementation. As technology advances, the integration of 3D printing into clinical environments is expected to grow, leading to more personalized and efficient healthcare solutions.

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